Microwave Remote Sounding of Atmospheric Composition – Some findings from MLS and future directions

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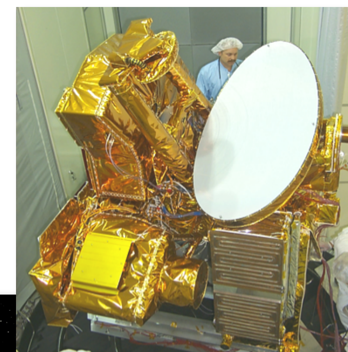
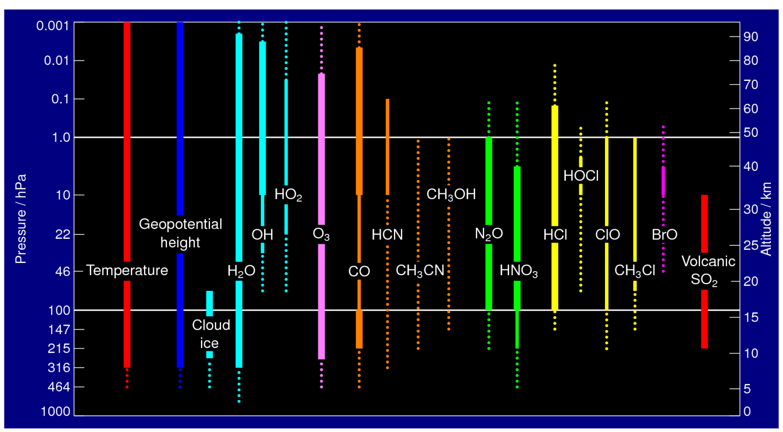
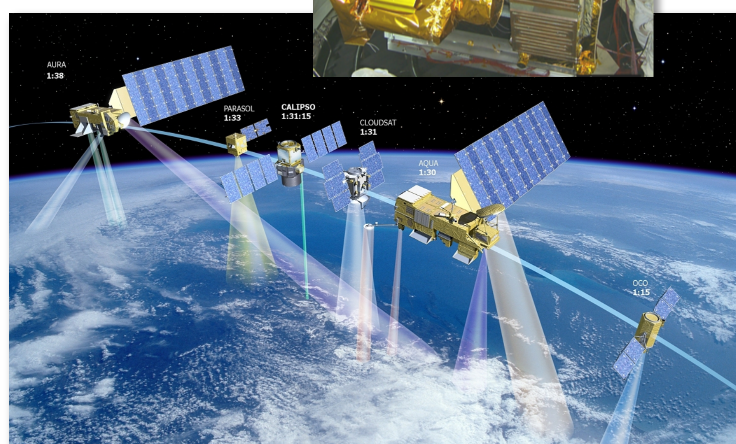


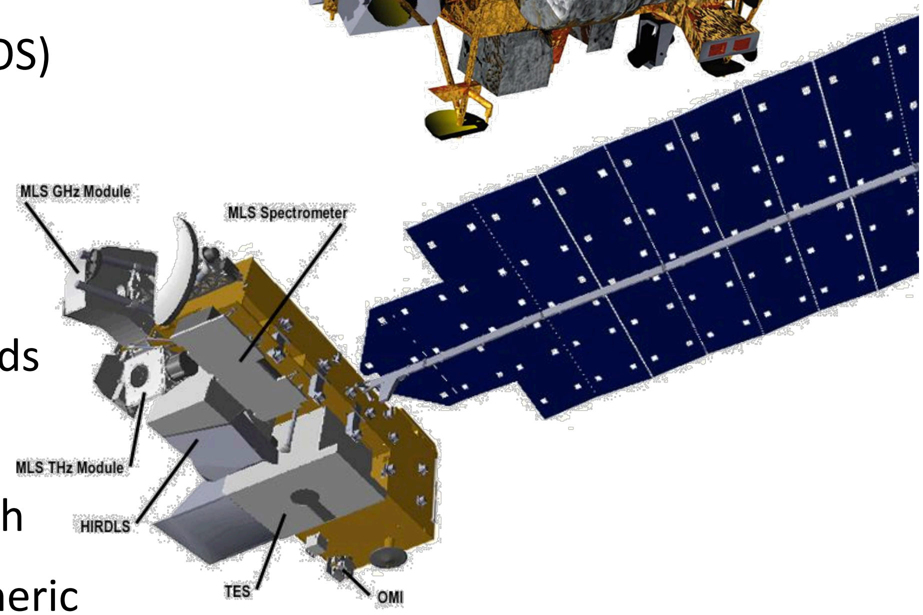




Outline of talk

- Introduction, overview of the microwave limb sounding technique
- MLS on the Upper Atmosphere Research Satellite (1991–2001)

- MLS on the Earth Observing System (EOS) Aura satellite (2004–)
- Selected highlights from Aura MLS
  - Stratospheric ozone
  - Upper tropospheric water and clouds
  - Upper tropospheric composition



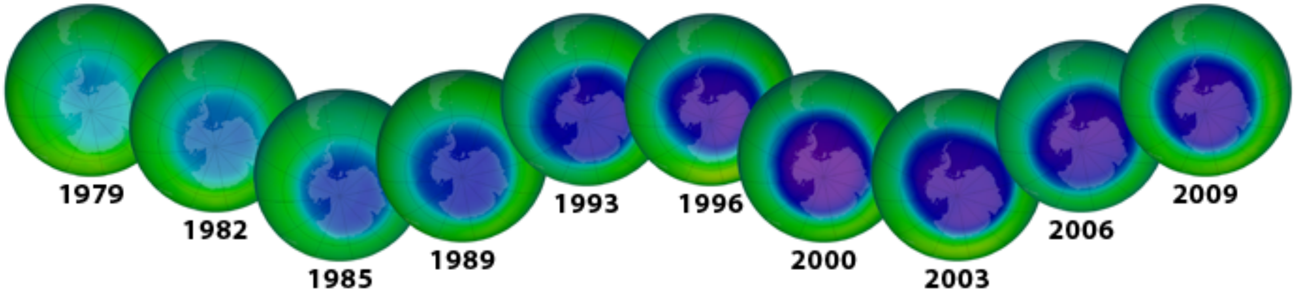
- Some recent Aura MLS-derived research
  - Six years of tropical upper tropospheric ozone, carbon monoxide and cloud ice measurements
- Beyond Aura: A brief look at future atmospheric composition missions and instrument concepts

Important issues in atmospheric composition

- Atmospheric composition is at the heart of many issues facing planet Earth:

Climate change – through changes in greenhouse gases and the impact pollution can have on cloud formation

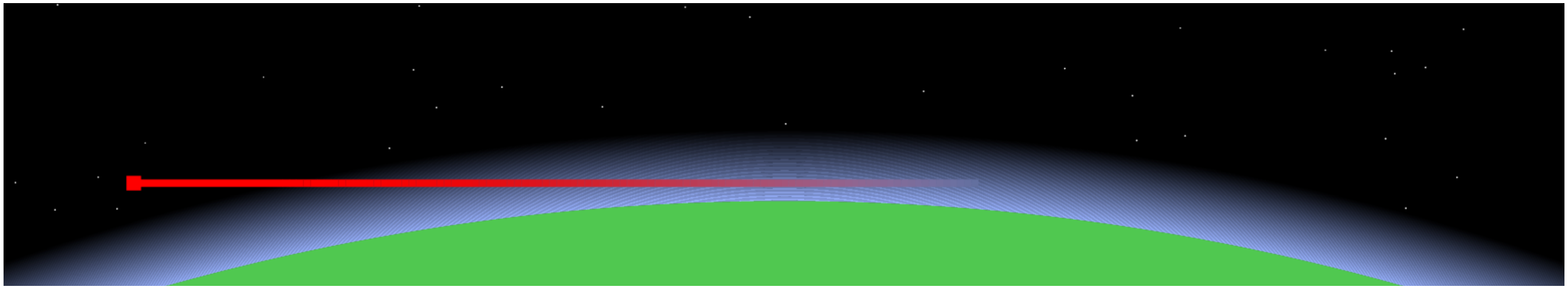
Ozone layer stability – anthropogenic emissions of long lived halogen species have directly led to depletion in stratospheric ozone, and to the Antarctic 'ozone hole'



Air Quality – biomass burning and anthropogenic pollution directly affect air quality. Intercontinental transport of pollution (e.g., Asia to California) makes this a global issue

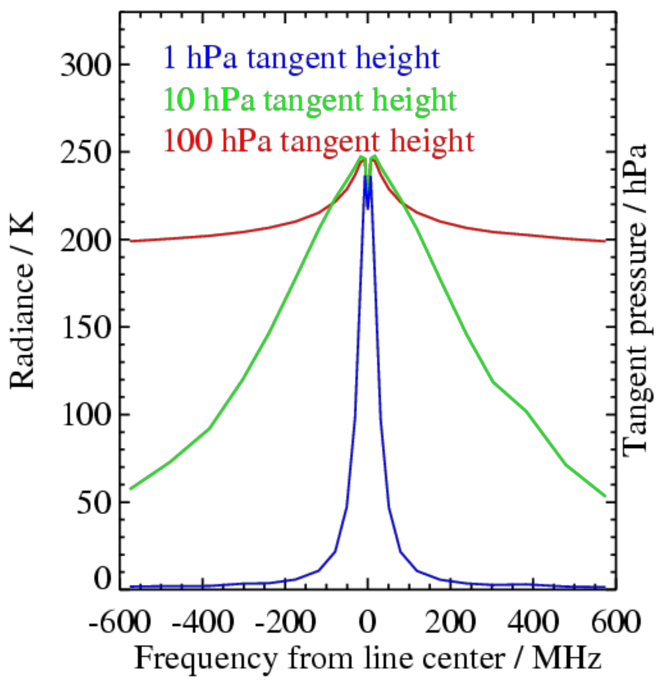
The Microwave Limb Sounding Technique

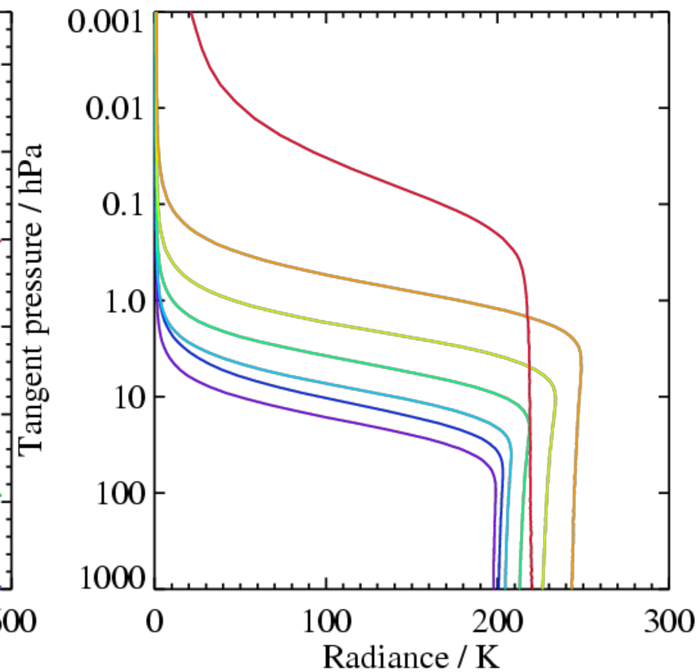
- The MLS satellite instruments observe thermal microwave emission from rotational lines of atmospheric molecules
- Limb viewing has several advantages over nadir sounding for composition:
  - Gives improved vertical resolution
  - It avoids issues of emissivity etc., when looking at Earth's surface
  - Longer ray path gives a stronger signal for trace species
  - In addition, microwave instruments are less sensitive to clouds than UV/Visible/IR instruments
- A disadvantage is that horizontal resolution is generally poorer
- Also, continuum absorption ultimately limits our information to the atmosphere above ~400 hPa



The nature of microwave limb signals

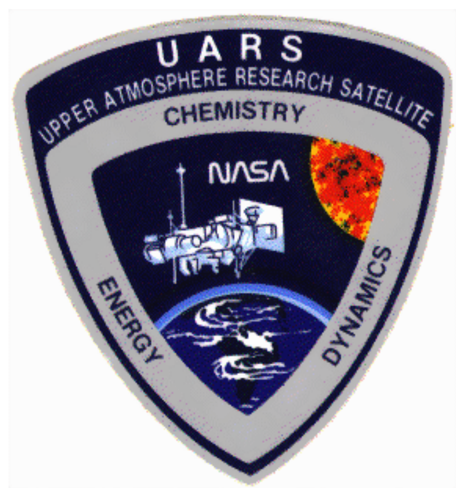
- MLS instruments are 'fancy radio receivers'
  - MLS instruments perform 'radio astronomy of the Earth'
- The frequency resolution is sufficient to resolve individual spectral lines
- Collision induced line broadening increases line width by ~3 MHz / mb
  - So, at 100mb (~16km), spectral lines are ~300 MHz wide

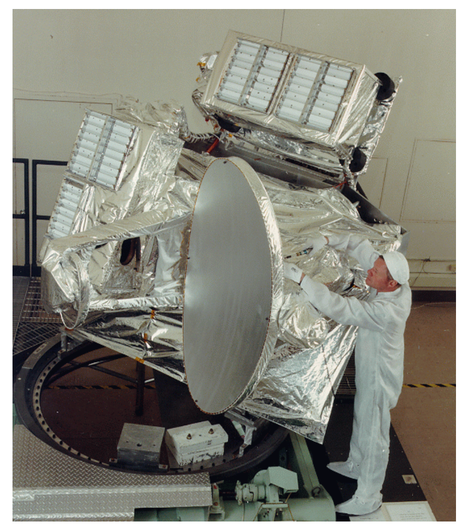




MLS on the Upper Atmosphere Research Satellite

- The first MLS was one of ten instruments on the Upper Atmosphere Research Satellite (UARS) launched in 1991
- UARS MLS operated for ~10 years (though observations became increasingly sparse from ~1995)
- The original scientific goal of UARS MLS was to improve understanding of stratospheric ozone chemistry in the upper stratosphere
- UARS MLS was designed to measure stratospheric O_3, ClO, and H_2O
- It also measured stratospheric HNO_3, Temperature, SO_2, and CH_3CN, upper tropospheric H_2O and cloud ice, and gravity waves





Background – The Antarctic Ozone Hole

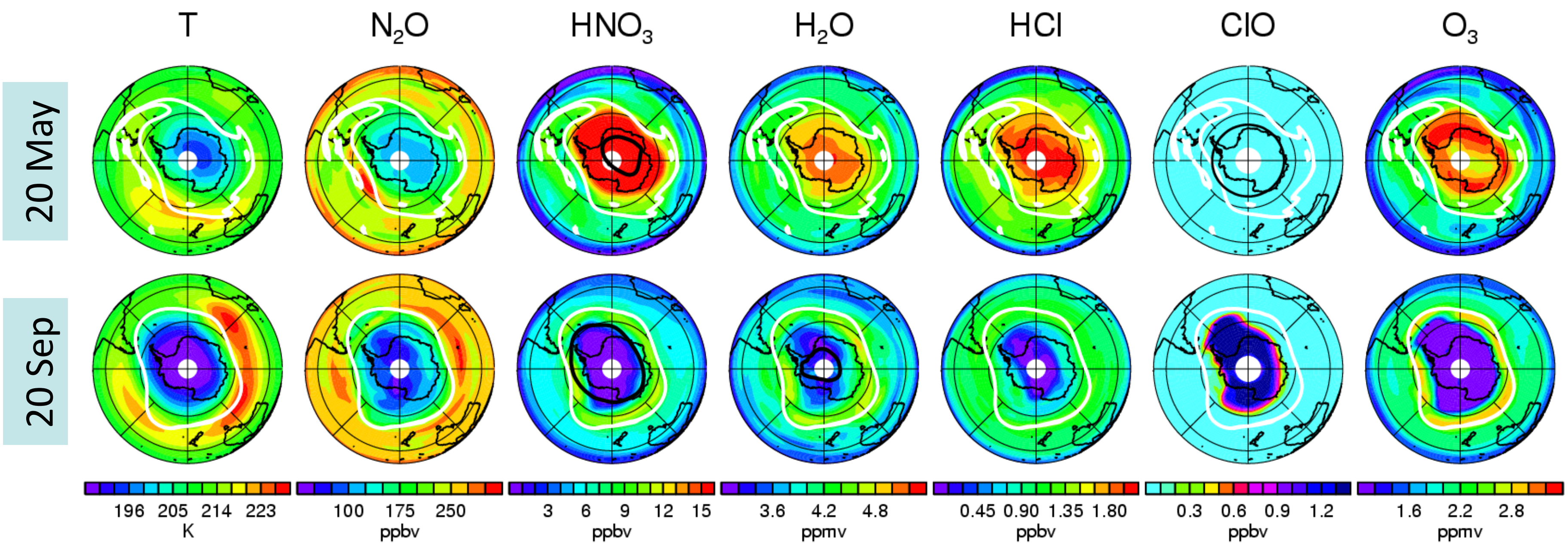
Low temperatures

and descending air

lead to formation of HNO_3 / H_2O clouds.

Reactions on the surfaces of these cloud droplets convert chlorine from ‘safe’ HCl into other forms including ‘ozone-depleting’ ClO,

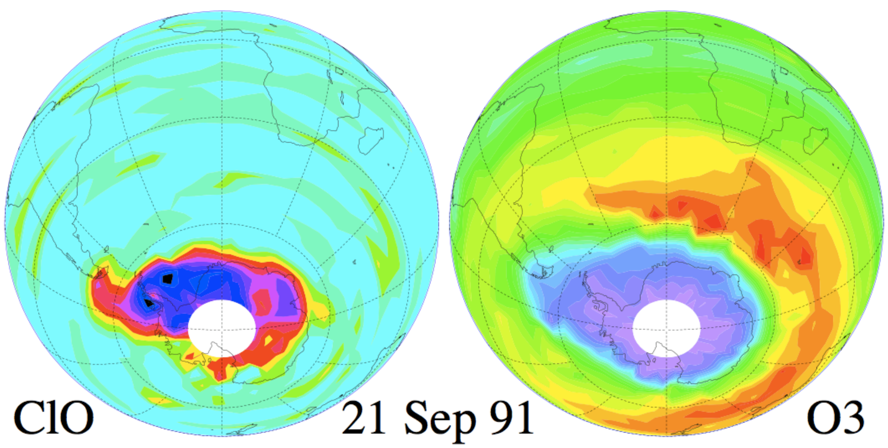
leading to chemical ozone loss.



Aura MLS observations from 2006

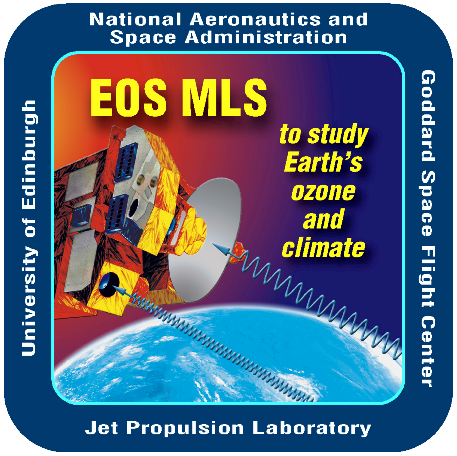
UARS MLS discovery – Arctic chemical ozone loss

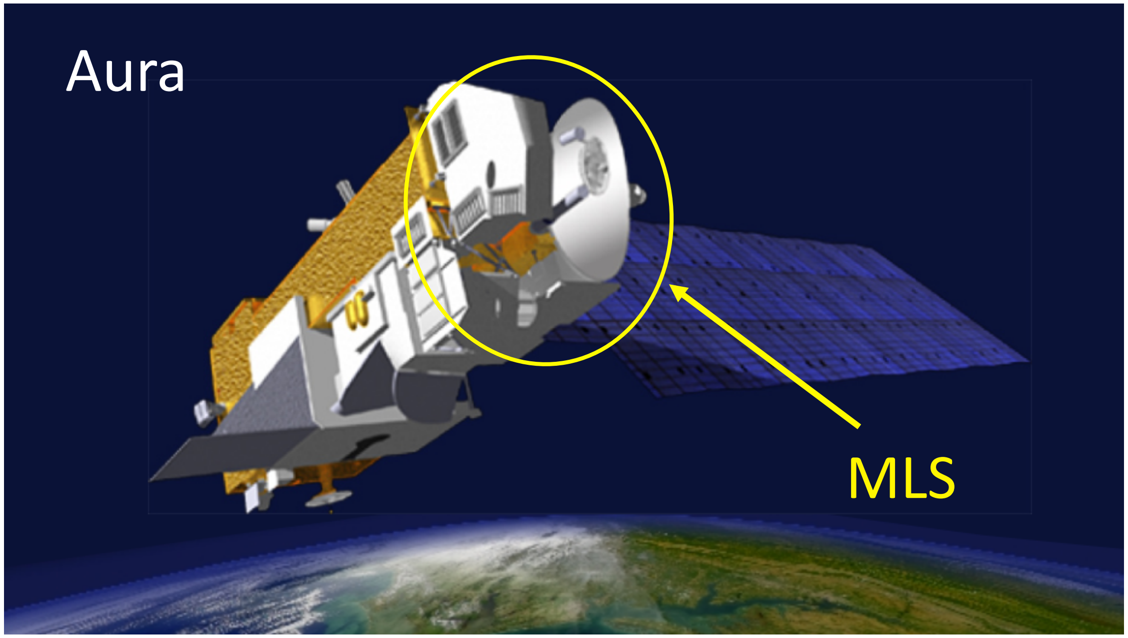
- The first day's observations from UARS MLS (below) showed enhanced ClO in the Antarctic polar vortex
- UARS MLS showed (right) that the Arctic polar vortex had as much chlorine activation as the Antarctic (albeit for a shorter period)

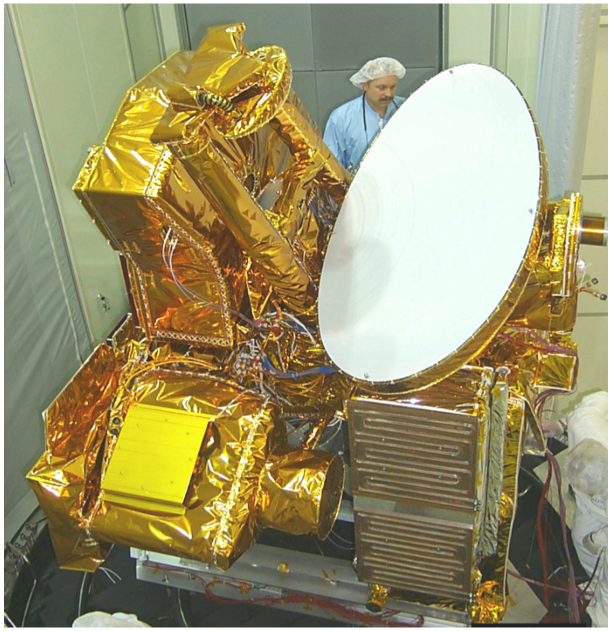


Aura Microwave Limb Sounder objectives

- Track the recovery of the ozone layer
- Understand aspects of how atmospheric composition affects climate
- Quantify aspects of pollution in the *upper* troposphere







NASA's Aura mission

- EOS Aura is the last of the three main NASA EOS missions
- Aura was launched from Vandenberg air force base in July 2004 carrying four instruments

High Resolution Dynamics Limb Sounder (HIRDLS)

- An infra-red radiometer for sounding the stratosphere, mesosphere and upper troposphere (heritage from LIMS, SAMS, ISAMS)

Microwave Limb Sounder (MLS)

- A microwave radiometer for sounding the stratosphere, mesosphere and upper troposphere (heritage from UARS)

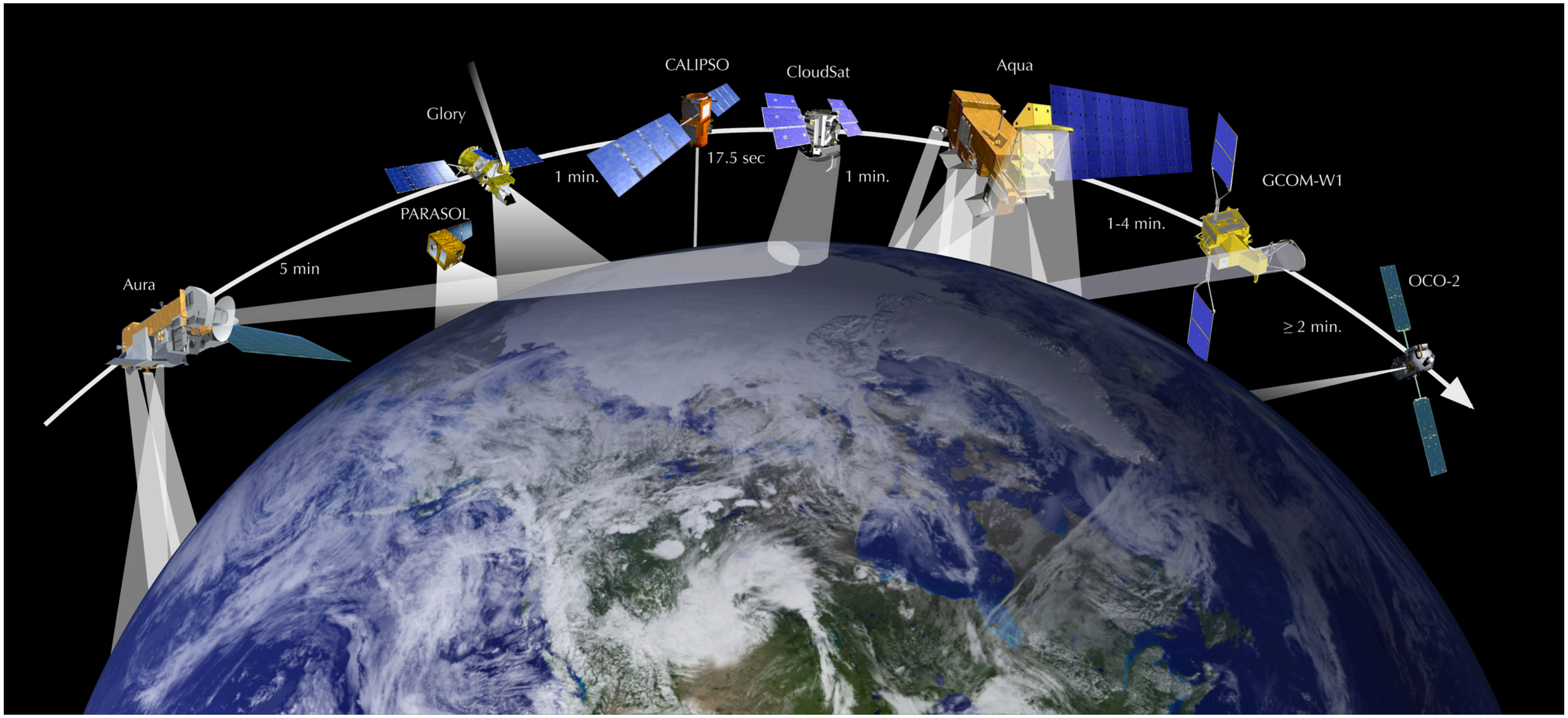
Ozone Monitoring Instrument (OMI)

- Measures column O_3, N_2O, SO_2 and other species from UV/Visible solar backscatter (heritage from TOMS)

Tropospheric Emission Spectrometer (TES)

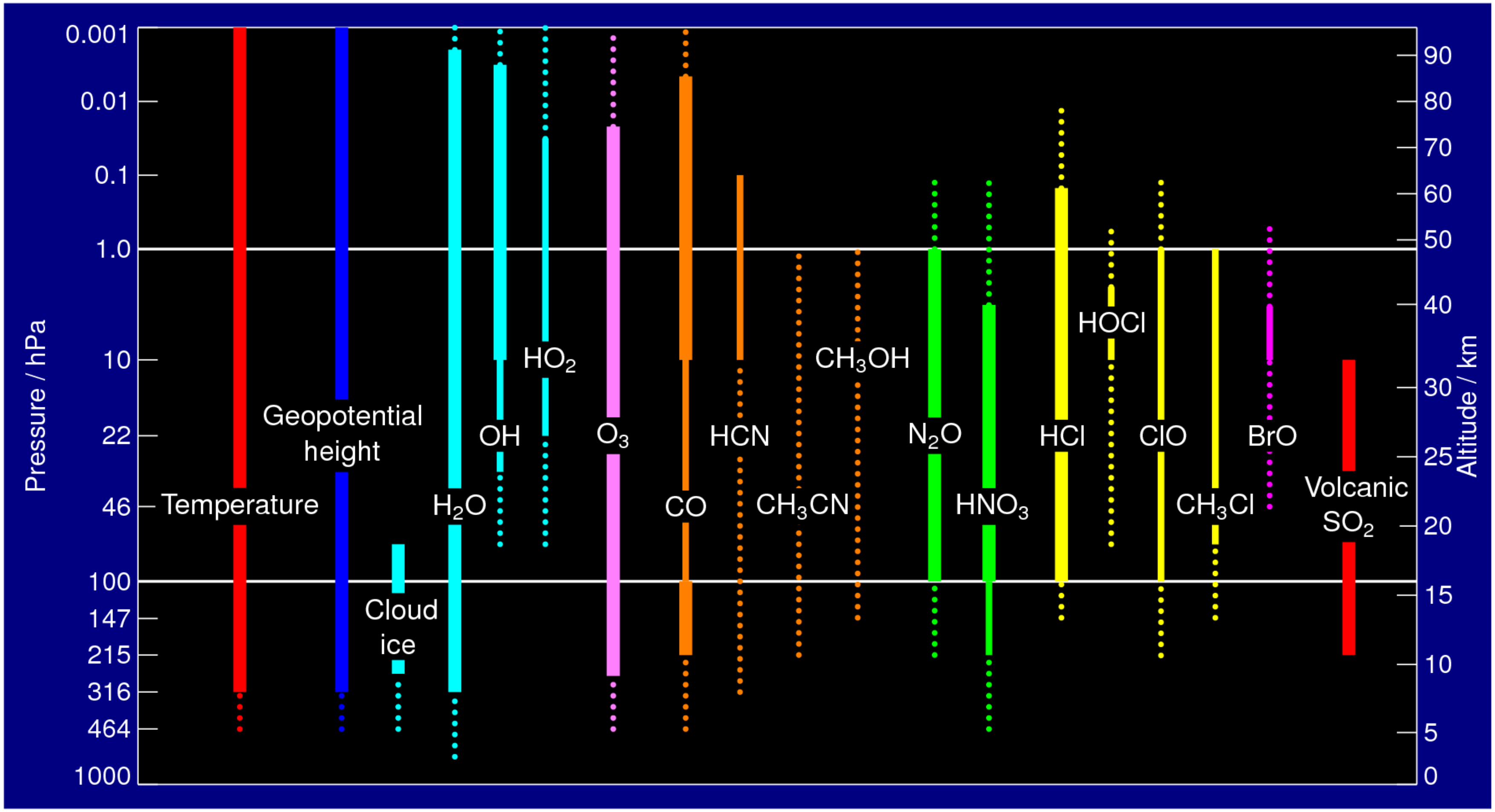
- An infrared limb and nadir viewing Fourier transform spectrometer for measuring tropospheric O_3, CO and other species

Aura's place in the polar orbiting 'A-train'



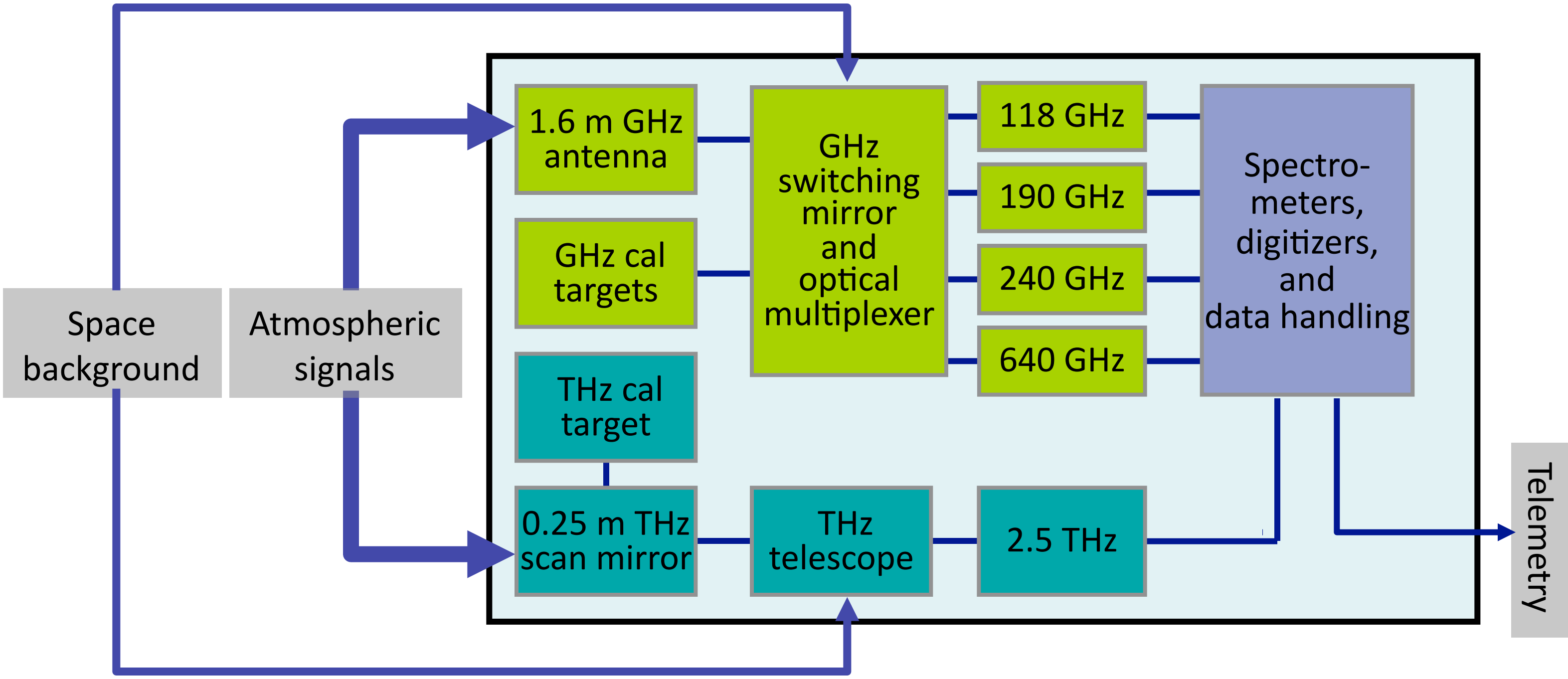
- The 'A-train' is a constellation of Earth observing satellites flying in formation
- The satellites all observe nearly the same air-mass (and/or ground pixels) within ~20 minutes of each other
- Glory, GCOM-W1 and OCO-2 are all in development
- Parasol has vacated its position in the A-train owing to fuel limitations

EOS MLS measurement objectives

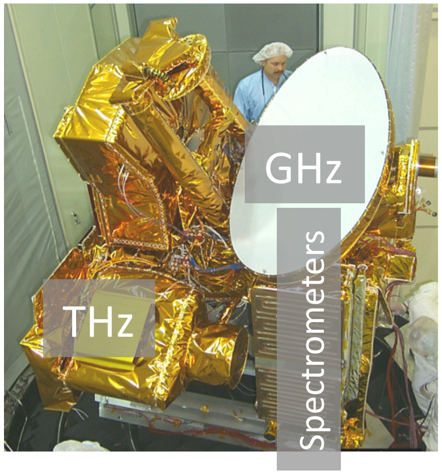


- Thinner lines indicate regions/products where averaging (e.g., zonal means) is required for useful signal to noise
- Dotted lines are goals for future versions of the MLS algorithms

The EOS MLS instrument



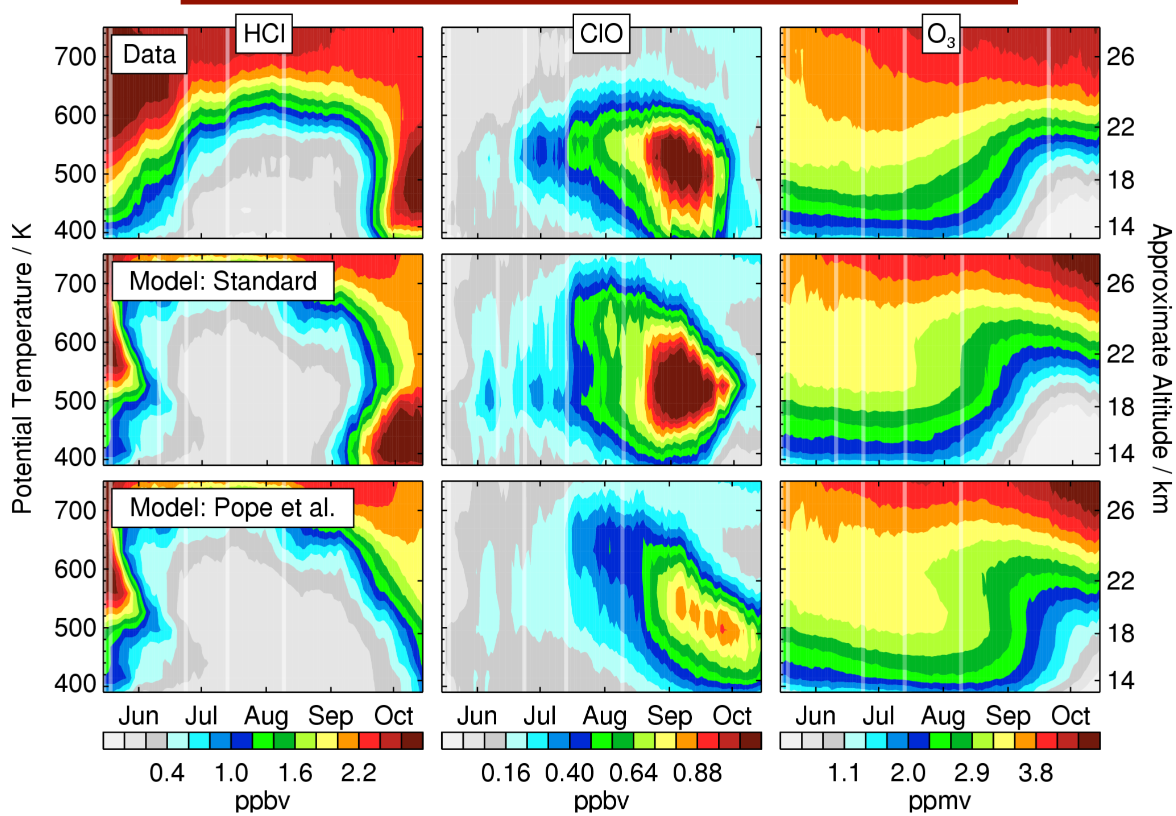
Receiver	Frequency	Main objectives
R1A, R1B	118 GHz	Temperature and pressure (from O_2)
R2	190 GHz	Upper tropospheric water vapor
R3	240 GHz	Upper tropospheric O_3, CO and cloud ice
R4	640 GHz	Stratospheric chemistry
R5H, R5V	2.5 THz	Stratospheric and mesospheric OH



Halogen chemistry in the polar lower stratosphere

- Recent laboratory measurements have called into question our theoretical understanding of chlorine-catalyzed polar ozone destruction
- When new parameters are used, models (e.g., SLIMCAT shown here) severely underestimate ClO during the peak activation period
- ClO also remains significantly enhanced well after MLS shows deactivation, especially at the lower levels
- Dramatic delay in deactivation also seen in HCl
- Substantially less ozone loss

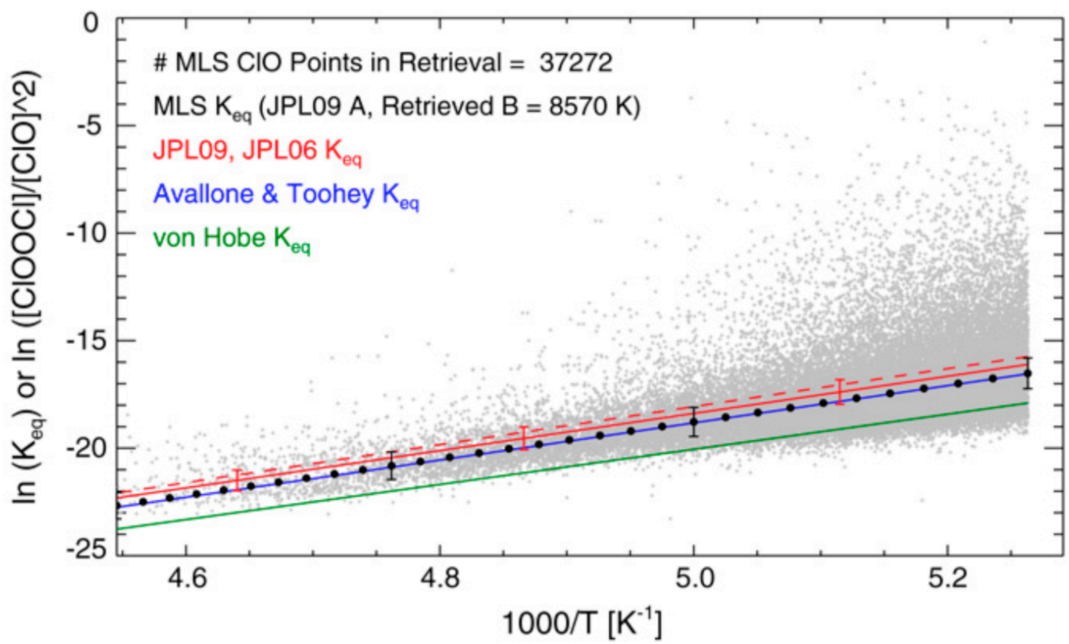
Antarctic vortex average profiles vs. time



[Santee et al., JGR, 2008]

Using MLS data to constrain chemical kinetics

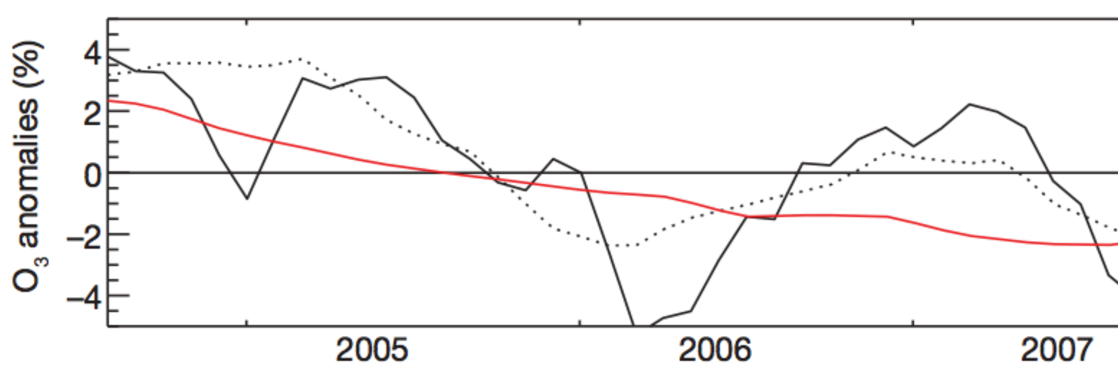
- MLS observations of enhanced ClO during polar night have placed new constraints on the equilibrium between ClO and the ClOOCl dimer (a key player in polar ozone loss)
- Laboratory quantifications of this equilibrium have to be extrapolated to the low temperatures found in the stratosphere
- Over 37,000 MLS nighttime ClO observations (grey points) were used to derive a new quantification for the equilibrium (black fitted points), with estimates of total inorganic chlorine (ClO_x) taken from the SLIMCAT model
- MLS observations were taken from seven winters (both Arctic and Antarctic)
- MLS results agree with some, but not all, laboratory data (red and green lines), and airborne observations (blue line)
- These findings are in line with theoretical expectations and arguably preclude any alternative mechanism with greatly dissimilar temperature dependence



[Santee et al., PNAS, 2010]

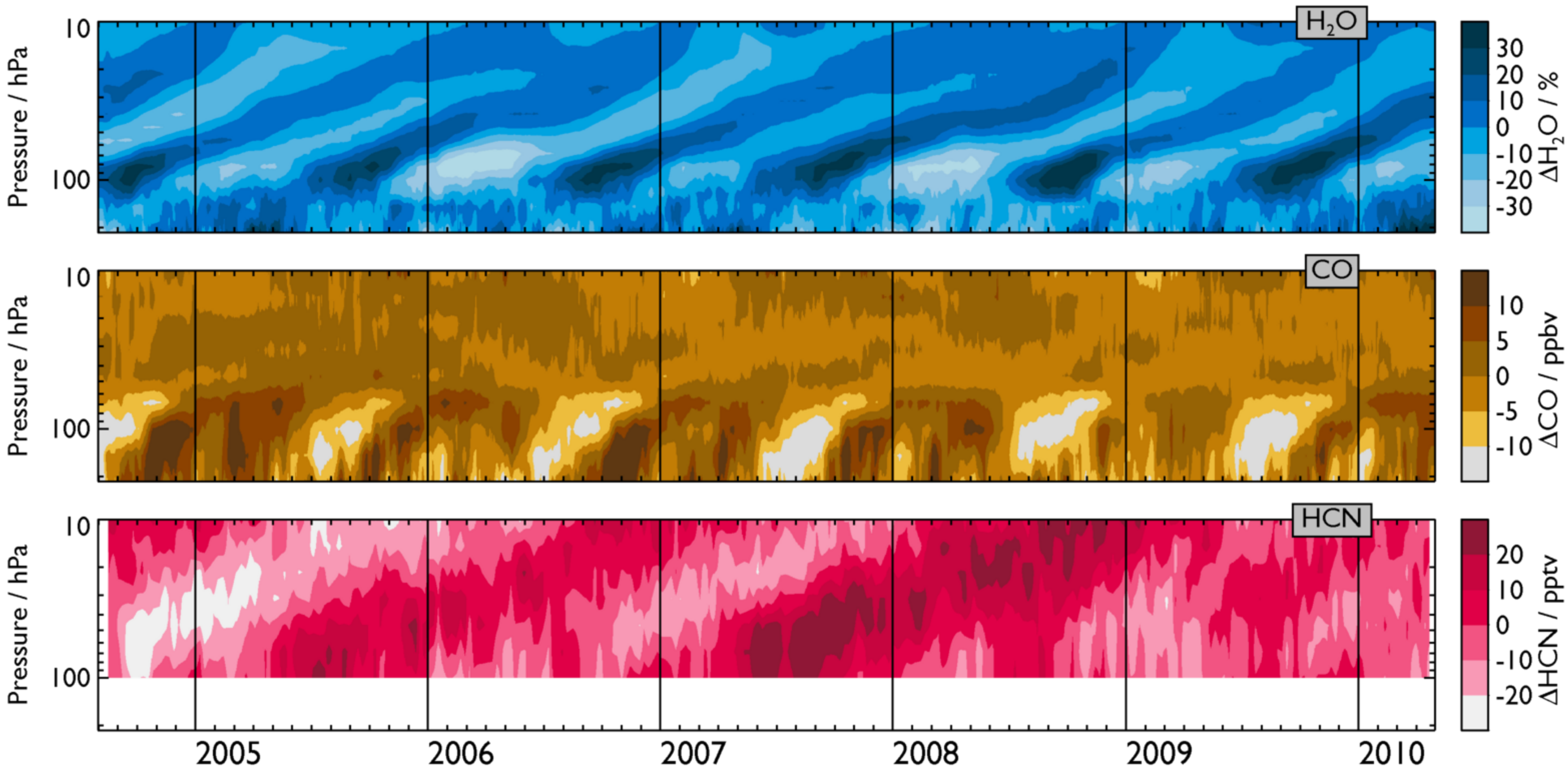
MLS ozone observations and solar variability

- Observations of 2004–2007 solar spectrum changes from the SORCE satellite challenge established models of the modulation of the solar spectrum by the solar cycle
- A recent paper *[Haigh et al., Nature, 2010]* shows that the 2004–2007 variations in stratospheric and mesospheric ozone observed by MLS are more consistent with the SORCE-observed solar spectral changes than the previously-expected spectral changes
- The paper also discusses how these findings have important implications for the accurate quantification of radiative forcing and hence climate
    - Properly accounting for changes in solar irradiance is essential for accurate anthropogenic radiative forcing estimates



Solid line shows deseasonalized MLS O_3 observations at ~32 km. Dotted line shows empirical model fit, while red line shows empirically fitted solar cycle contribution. This contribution is statistically significant, and shown to be consistent with SOURCE-derived changes in solar spectrum

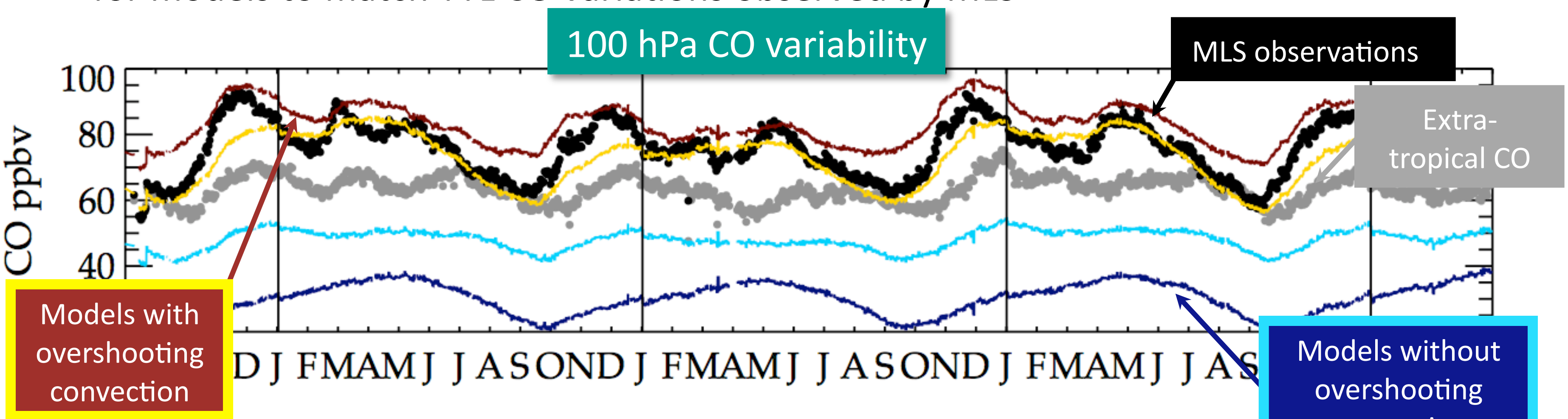
MLS observations of ‘tape recorders’



- Several atmospheric ‘tape recorder’ phenomena have been discovered by MLS
  - Water vapor, e.g., *Read et al., ACP 2008* (discovered by UARS MLS)
  - Carbon monoxide – *Schoeberl et al., GRL 2006*
  - Hydrogen cyanide – *Pumphrey et al., GRL 2008*

MLS gives insights into TTL processes

- MLS H_2O and CO observations have led to improved understanding of processes in the Tropical Tropopause Layer (TTL)
- H_2O observations confirm the role of the cold point tropopause in controlling stratospheric humidity
- However, overshooting convection (above the level of neutral buoyancy) is needed for models to match TTL CO variations observed by MLS

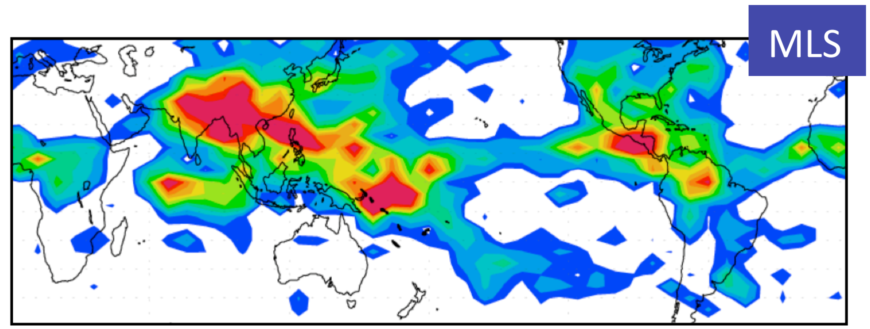


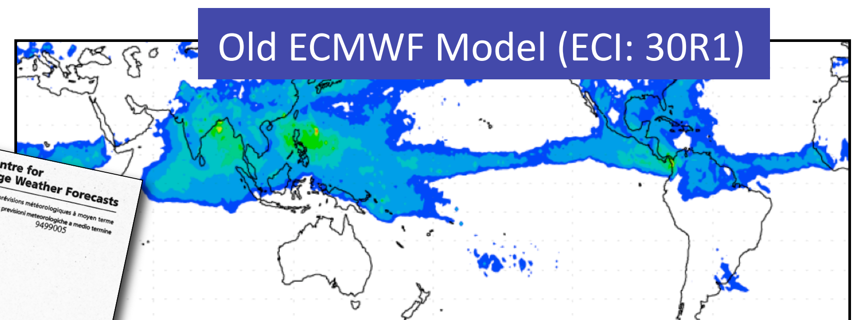
- See *Read et al., [2008, ACP]* for more discussion
  - Including the use of ACE-FTS HDO to provide further constraints on cloud ice lofted by the overshooting convection
  - Also, discussion of factors affecting trends in stratospheric humidity

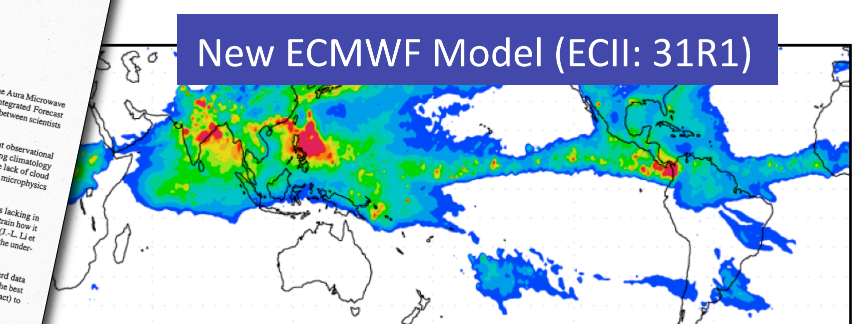
MLS Cloud Ice data and ECMWF model

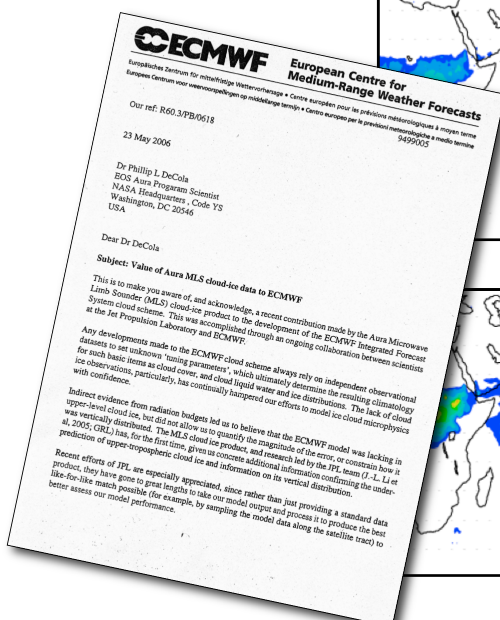
- Maps show July 2006 cloud ice water content (IWC) at 215 hPa
- MLS provided the first global measurements of this poorly understood key climate parameter
- New CloudSat and CALIPSO data complement MLS measurements
- They measure large and smaller cloud particles than MLS
- ECMWF used MLS IWC data to help justify changes in cloud microphysics
- This led to notable improvements in modeling of the location and intensity of tropical thunderstorms

[Frank Li et al., GRL, 2005]









ECMWF European Centre for Medium-Range Weather Forecasts

Europäisches Zentrum für mittelfristige Wettervorhersage • Centre européen pour les prévisions météorologiques à moyen terme
Europees Centrum voor weervoorspellingen op middellange termijn • Centro europeo per le previsioni meteorologiche a medio termine

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Our ref: R60.3/PB/0618

23 May 2006

Dr Phillip L DeCola
EOS Aura Prograram Scientist
NASA Headquarters , Code YS
Washington, DC 20546
USA

Dear Dr DeCola

Subject: Value of Aura MLS cloud-ice data to ECMWF

This is to make you aware of, and acknowledge, a recent contribution made by the Aura Microwave Limb Sounder (MLS) cloud-ice product to the development of the ECMWF Integrated Forecast System cloud scheme. This was accomplished through an ongoing collaboration between scientists at the Jet Propulsion Laboratory and ECMWF.

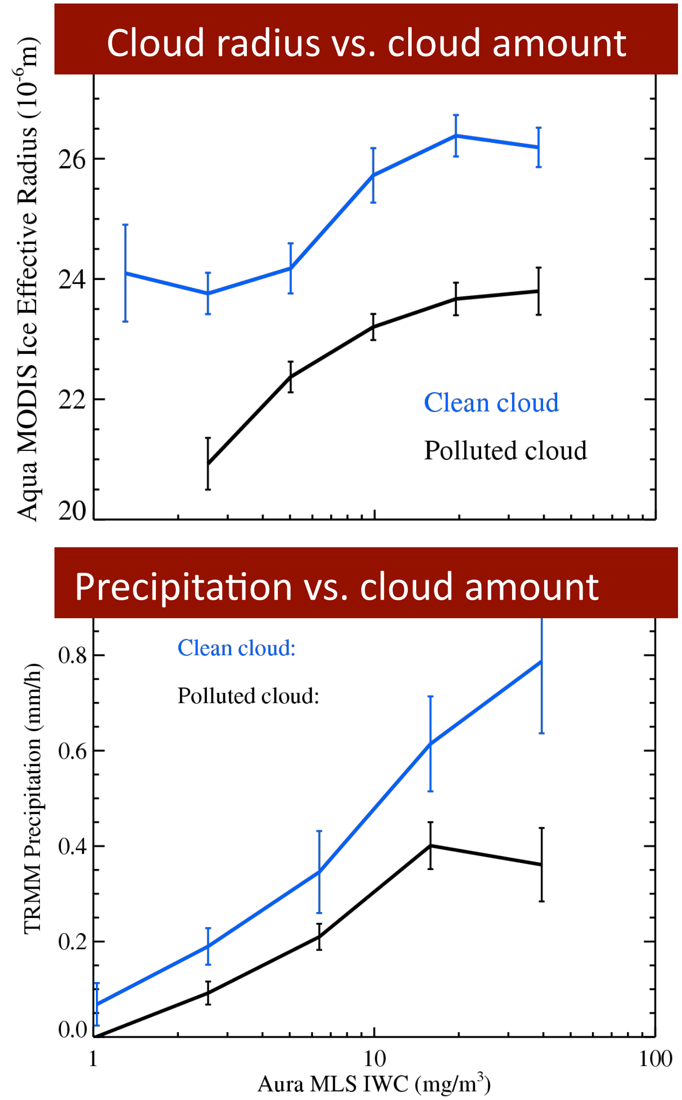
Any developments made to the ECMWF cloud scheme always rely on independent observational datasets to set unknown 'tuning parameters', which ultimately determine the resulting climatology for such basic items as cloud cover, and cloud liquid water and ice distributions. The lack of cloud ice observations, particularly, has continually hampered our efforts to model ice cloud microphysics with confidence.

Indirect evidence from radiation budgets led us to believe that the ECMWF model was lacking in upper-level cloud ice, but did not allow us to quantify the magnitude of the error, or constrain how it was vertically distributed. The MLS cloud ice product, and research led by the JPL team (J.-L. Li et al, 2005; GRL) has, for the first time, given us concrete additional information confirming the under-prediction of upper-tropospheric cloud ice and information on its vertical distribution.

Recent efforts of JPL are especially appreciated, since rather than just providing a standard data product, they have gone to great lengths to take our model output and process it to produce the best like-for-like match possible (for example, by sampling the model data along the satellite tract) to better assess our model performance.

Observations of the aerosol indirect effect

- Aerosol-indirect effects – the impact of aerosol pollution on cloud properties – are one of the largest uncertainties in climate predictions
- Global studies of this are hampered by our inability to remotely sense aerosols in the presence of cloud
- In some seasons and regions, MLS CO observations can be used as a proxy of aerosol pollution
- Over south America in June – October, polluted clouds are seen to be associated with smaller particle sizes and lower precipitation than 'clean' clouds
- Such observations are being used in new parameterizations of aerosol indirect effects in climate models



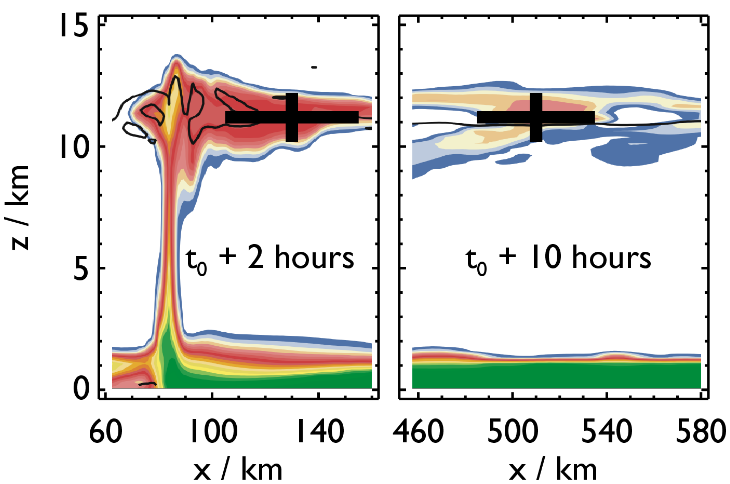
[Jonathan Jiang et al., GRL, 2008]

MLS observations of upper trop. O_3, CO, Cloud ice

This part of the talk is in a separate file

Outstanding science questions in the UT/LS

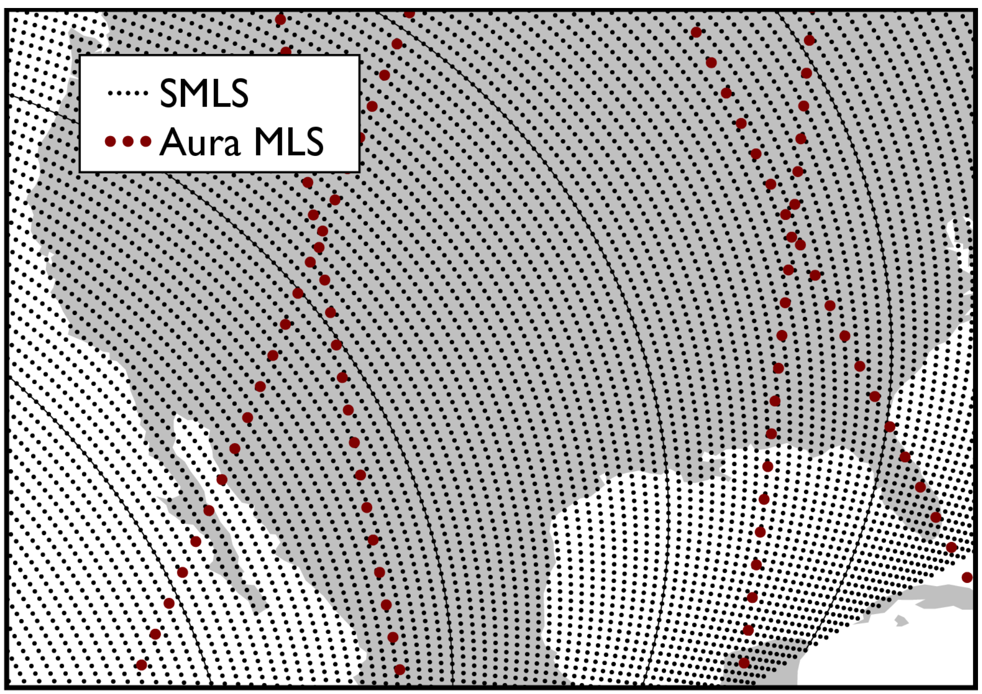
- MLS UT/LS observations are providing information needed to quantify critical processes affecting climate, ozone layer stability and air quality
- However, these observations lack the temporal and spatial resolution needed to quantify important processes with small length and time scales
- Notable among these is deep convection which, on timescales of hours, rapidly transports air from the (potentially polluted) boundary layer into the UT
  - Convection dominates the budgets of upper trop. O_3, H_2O, & cloud ice
  - Convection has a significant diurnal cycle, peaking strongly in the afternoon over land and weakly during the night over oceans

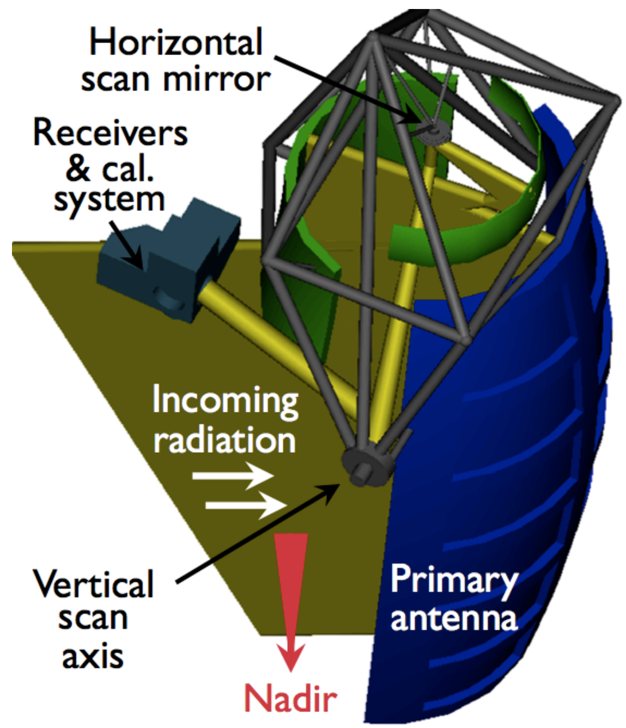


Deposition of boundary layer air into the upper troposphere. Model predictions from *Mullendore et al.* [JGR, 2005] with crosses added to show the SMLS resolution. Color indicates the abundance of a boundary layer tracer at 2 and 10 hours into a convective simulation.

The Scanning Microwave Limb Sounder

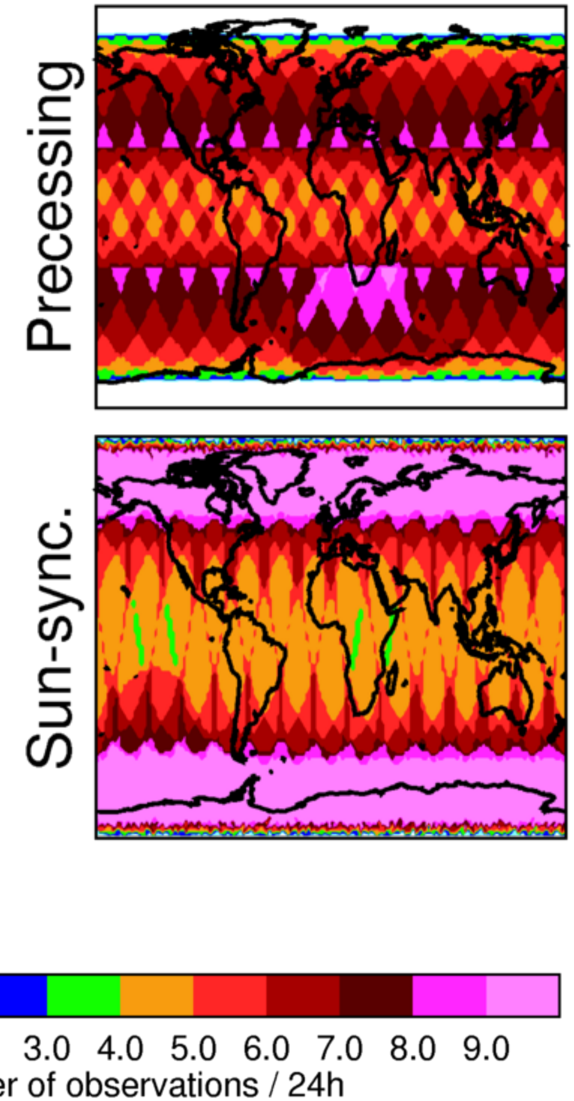
- The Scanning Microwave Limb Sounder (SMLS) is a new instrument concept that provides the needed high spatial / temporal resolution observations of the upper troposphere and lower stratosphere
- SMLS adds azimuth-scanning, combined with low-noise 'SIS' receivers
  - As used in ground-based and airborne applications for ~20 years, enabled by newly-available flight-qualified 4 K coolers
- This gives 50 x 50 km horizontal sampling



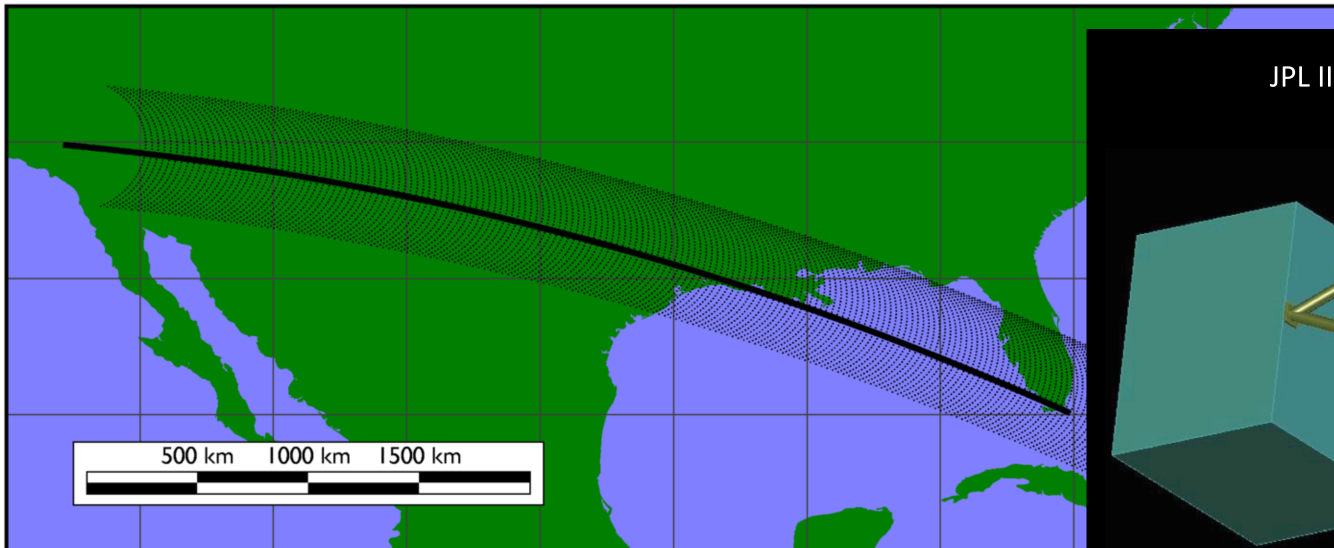


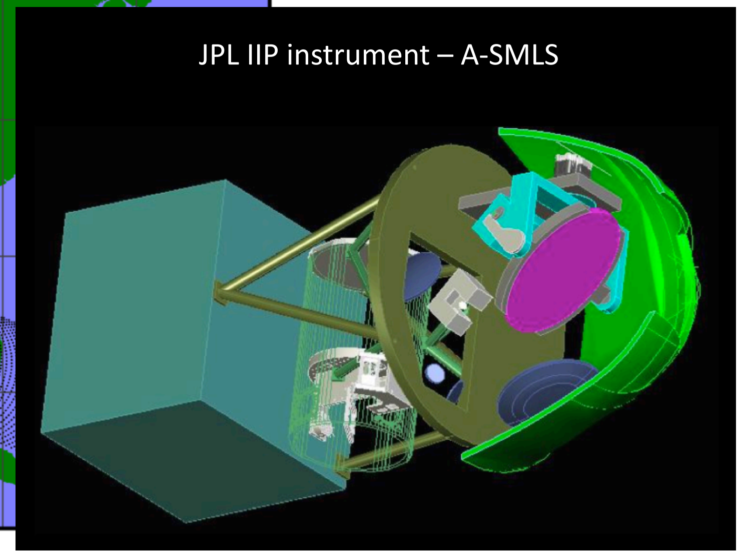
SMLS temporal resolution

- The ±65° SMLS azimuth scan gives a ~5500km-wide swath from an 830 km orbit
- This views ~45% of the globe on <u>every orbit</u>
- Such coverage offers dramatic improvements in temporal resolution over earlier instruments
- For example, in a 52° inclined orbit SMLS would make 7 to 9 measurements daily at mid-latitudes
  - Such measurements precess earlier in local time each day, covering the entire diurnal cycle in ~36 days
  - Such temporal resolution is needed to quantify critical 'fast processes' affecting composition and climate, notably convection
- An airborne prototype of SMLS is being developed
  - This will be able to view a ~300 km-wide swath from a high-altitude aircraft



An airborne SMLS instrument





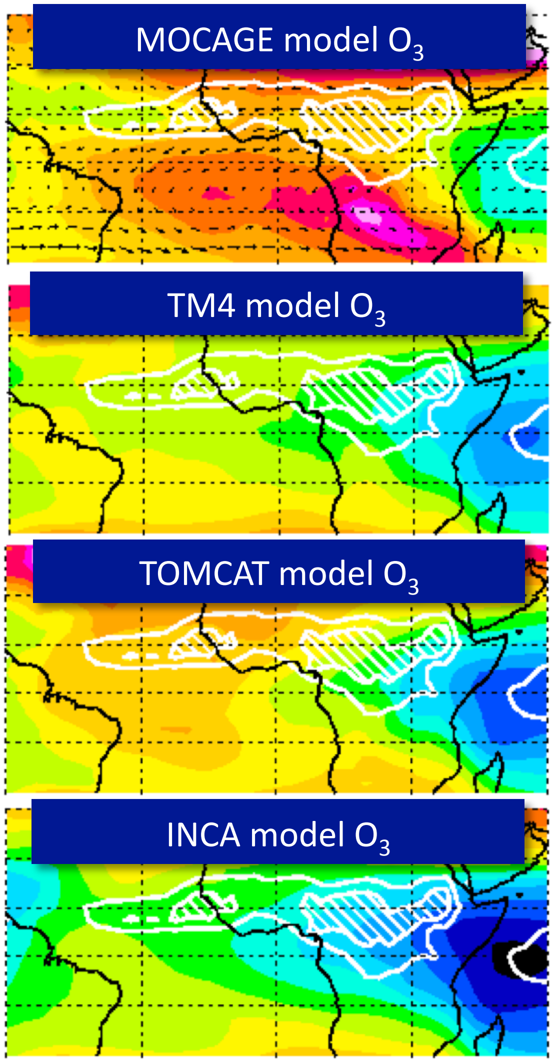
- From 60 kft (20 km) altitude (such as from the Global Hawk), an airborne limb sounding instrument can view a 450 km-wide swath at 12 km, with a nominal 20x10 km horizontal resolution (along x cross track)
- We are developing this instrument under the NASA IIP program, targeting the WB-57 or Global Hawk platforms
- We expect a signal to noise ~4x better than that for Aura MLS
- Targeting measurements useful for improving understanding of convective outflow, long range pollution transport, and stratosphere / troposphere exchange events

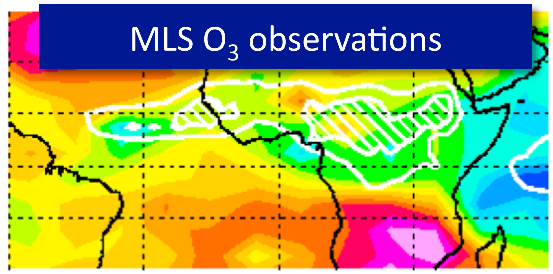
Summary and future work

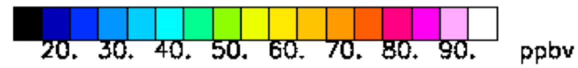
- Aura MLS makes daily global observations of more than 18 species
- These observations have been made on an essentially uninterrupted basis for the six years since launch
- MLS data have been used in ~250 peer-reviewed scientific publications
  - More than half have been led by scientists outside the ‘core’ MLS team
  - We welcome your involvement!
- A ‘near real time’ version of the MLS dataset (initially O_3 and Temperature) are generated for use in data assimilation, weather forecasting, and field flight planning
- Version 3 of the MLS data processing algorithms are now in production
  - Main focus is improving data quality in the upper troposphere (notably for CO and HNO_3) and stratosphere (for ClO) and to add CH_3Cl as a new product
- Future plans for the MLS data include improvements to measurements in the presence of cloud and extension of products to lower in the atmosphere
- An advanced ‘Scanning Microwave Limb Sounder’ (SMLS) instrument concept is under development, including an airborne prototype

Backup material starts here

Convective transport and lightning in models





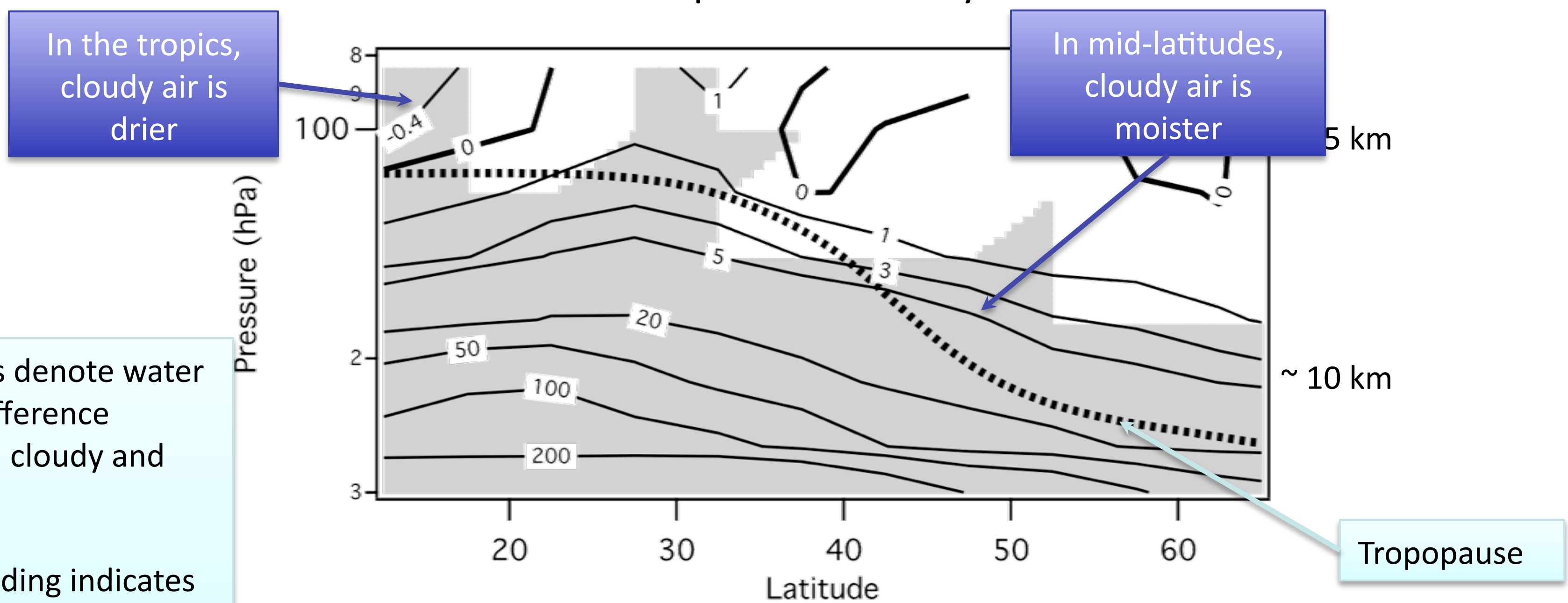


[Brice Barret et al., ACP, 2010]

- Deep convective thunderstorms dominate the budgets of ozone, carbon monoxide etc., in the tropical upper troposphere
- Lightning-generated NO_x emissions act to increase ozone abundances downstream of convection
- MLS observations are a unique source of daily global high-vertical resolution observations in this altitude region, where water vapor and ozone are strong greenhouse gases
- MLS ozone observations (above) are being used to validate the convective transport (and lightning) schemes used in state of the art chemical transport models (left)

Capitalizing on the power of the A-train

- MLS water vapor observations cover the upper troposphere and lower stratosphere (an excellent complement to AIRS observations of the mid- and lower-troposphere)
- MLS observations are made within 10 km of CloudSat and CALIPSO cloud soundings enabling new multi-instrument stuies
- Differences between MLS measurements of water vapor in clear-sky and cloudy regions (as determined by collocated Calipso observations) give insights into the possible influences of clouds on stratospheric humidity



Contours denote water vapor difference between cloudy and clear sky

Grey shading indicates that differences are significant at >95%

[Andrew *Dessler, 2009, JGR]*